Properties of galactic bars in the Sloan Digital Sky Survey

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Bars are a common structure that is found in about half of spiral galaxies and are observed independently of Hubble type.

According to the theoretical studies of bars, bar instability occurs in a self-gravitating and cold disk which is supported by rotation, and resulting non-axisymmetric features cause the infall of gaseous materials to the center of galaxies and the active star formation there. Furthermore, it is known that while the mass concentration to the galactic center destroys a bar, it can be reformed by the external gas accretion. Through these processes the star formation is enhanced in the galactic center, which can lead to the bulge growth and formation. This process of galaxy formation is called the secular evolution scenario.

In observational studies of barred galaxies, photometric properties such as bar structures and light profiles as well as chemical abundance gradients have been studied. However, they were not sufficient to make clear the formation of barred galaxies or the evolution of the bar itself, because the past studies used a small number of galaxies in their samples and/or a subjective method of analysis such as a bar detection by the visual inspection.

Therefore, we aim to study the structural parameters and colors of galactic components (the bar, bulge and disk) of barred galaxies statistically and objectively, to investigate the formation of barred galaxies. We use a large number of galaxies from the Sloan Digital Sky Survey (SDSS), which is a large-scale project covering one quarter of the entire sky and use a quantitative method of detecting bars, for which we make the original programs which fit the isophotes of galaxies to a series of ellipses (ellipse fitting) and detect bars automatically.

The SDSS produces both imaging and spectroscopic surveys. The imaging camera consists of 30 2048×2048 CCDs, placed in an array of six columns and five rows. The telescope's scanning is aligned with the columns. Each row observes the sky through a different filter, in temporal sequence *r, i, u, z* and *g*. Spectra are obtained using a multi-object spectrograph which observes 640 objects at once. In July 2005, the SDSS released the Data Release 4 (DR4) which includes the latest results of its observation.

We selected 28,504 galaxies from the SDSS-DR4 using the criteria that the Petrosian magnitude (m_p) in i-band is smaller than 15.5 mag, the Petrosian radius in i-band is larger than 10.0 arcsec, and the redshift is less than 0.1. These parameters are taken from the database of the Catalog of Archive Server (CAS), where the reduced data of imaging and spectroscopy in the SDSS are stored. Out of these galaxies, we selected 6,133 disk galaxies using the criterion that the concentration indices in both i- and r-bands, which are the ratio of r_{90} to r_{50} in each band from CAS, are smaller than 2.5, following the result of Shimasaku et al. (2001). Here r_{90} and r_{50} are respectively the radius containing 90% and 50% of the total luminosity.

The ellipse fitting method is used to detect a bar from i-band galactic images. We devised our program to fit ellipses to galaxy isophotes following the algorithm developed by Jedrzejewski (1987). We calculate the inclination (i) of the galaxy using the ellipse whose intensity (μ) is $\sim 3\sigma$ above the sky. We selected galaxies with a low

inclination ($i \leqq 45^\circ$) to minimize possible projection effects that could produce source confusion in the inner regions of the galaxies. After applying this selection, we are left with 2,542 galaxies. From the radial profiles of the ellipticity and the position angle of isophotes obtained by ellipse fitting for each galaxy, we detect bars by assuming that a bar is the most elongated linear structure in the host galaxy having a substantial range in radius. As a result, we get 828 barred galaxies, which is 32.6% of 2,542 face-on spiral galaxies. Bars are detected with a nearly constant rate of 28.9~36.1% except for the magnitude range $11.5 \leqq m_p \leqq 12.5$, where the number of galaxies is small.

First, we checked the structural properties of the bars. In other observational studies, it is found that the bars in earlier-type galaxies have a larger relative bar length, the bar ellipticities and the Hubble types have no correlation, and the relative bar lengths increase with the bar ellipticities. In our sample, we confirmed these results, though the dispersions of our correlations are smaller than theirs. It is thought that this is caused by a difference in the way to detect a bar. Instead of the Hubble type, we use the concentration index (C_{31}), which is another morphological parameter of a galaxy. C_{31} is the ratio of r_{75} to r_{25}, which are the major-axis lengths of the ellipses containing 75% and 25% of the total luminosity. The relative bar length increases with C_{31} in i-band, although the dispersion of this correlation is very large. Weakness in correlation seems to be caused by the reasons that the concentration of a galaxy is only one of the criteria used for classifying that a galaxy into the Hubble type and that C_{31} and the Hubble type do not obey a well-defined linear relation but C_{31} has similar values for Hubble types later than ~Sbc.
The bar ellipticity is also independent of C_{31} in i-band, which is consistent with the result where we used the Hubble type.

Second, we investigate the colors g-r and r-i of barred galaxies after K-correction. We calculate the K-correction using the software developed by Blanton et al. (2003), which is distributed publicly. We apply this soft to each component of the galaxy such as the bar, the bulge and the disk, and get corrected luminosities and colors of each component. There is a possibility that we cannot observe faint higher redshift galaxies, i.e., the galaxies with high luminosities are selected preferably. To avoid this selection effect, we set the redshift and the absolute magnitude limits to our sample. Applying the limits of $z \leqq 0.04$ and $M \leqq -20.74$ mag in i-band to our sample, we get a complete sample of 132 barred galaxies, from our sample. The typical errors of the total, the bulge, the bar and the disk g-r colors are 0.082, 0.065, 0.106 and 0.111 mag, respectively for this sample. We obtain a tendency that the bulge and the disk are the reddest and bluest in each galaxy, respectively, while the bar has intermediate colors. The mean g-r color of the bulges is ~0.75 mag, that of the bars is ~0.67 mag, that of the disks is ~0.56 mag and that of the total is ~0.61 mag.

We find that there are color magnitude relations in the components of the bulge and bar, while the disk colors and magnitudes have no correlation. This suggests that the more luminous the bulges and the bars are, the redder colors they have. Colors show a significant correlation with the concentration of host galaxies, which indicates that the redder the colors of each component are, the higher the concentration is. This correlation is traced back to the color-magnitude relation for each component, because the absolute magnitude of each component and the host galaxy concentration have a good correlation. Colors of bulges ave a weak correlation with the bar parameters which indicates that galaxies with bluer bulges have stronger bars. This may indicate that bars have a role in changing the colors in the central region of galaxies by the enhancement of star formation there. The color difference between the bulges and the bars and the bar strength has no correlation except the galaxies with $C_{31}<2.5$. The galaxies with $C_{31}<2.5$ have a correlation that for the galaxies with stronger bars, the bulges are bluer than the bars. We study the relation of the color difference between the bulges and the bars and the concentration of galaxies. This result seems to have a correlation that the galaxies with higher concentration have the smaller color difference. On the other hand,

the color difference between the bars and the disks has no correlation with the strength of a bar. There is a very weak trend that the higher the concentration is, the smaller the color difference is.

Finally, to investigate and interplet the color differences between three components, we use the models of the stellar population synthesis by Bruzual & Charlot (2003). Assuming that the star formation rate is given by the delayed SFR model, we compare the model colors at 13.75 Gyr with the observation changing the timescale (τ) of the SFR and the metallicity (Z). We use τ = 0.1, 0.5, 1, 2, 3, 4, 5, 6, 9, 12 and 20 Gyr, and Z = 0.0001, 0.0004, 0.004, 0.008, 0.02 and 0.05. We fit the observed colors of every galaxy to the models by interpolating the model grids of τ and Z. The mean of fitted (τ , Z) is (2.48 Gyr, 0.0052), (2.34 Gyr, 00046) and (3.06 Gyr, 0.0054) for the bulges, the bars and the disks, respectively, while some bar and bulge colors are too red to fit to the models. Most galaxies of our sample have a smaller τ of the bar than τ of the disk. This indicates that the stellar population of the bar is formed earlier than the disk, which is consistent with the picture that the star formation has continued in the outer part of the galactic disk even after the inner part developed into a bar. The difference of τ between the bulge (τ_{Bulge}) and the bar (τ_{Bar}) is typically less than $\sim$2 Gyr. In the galaxies with $\tau_{Bulge} > \tau_{Bar}$, the bars may have played a role in causing the star formation in the central region of galaxies. The stronger the bar is, the larger τ_{Bulge} τ_{Bar} is on the average. Moreover, in the galaxies with $\tau_{Bulge} > \tau_{Bar}$, a large equivalent width of H α is observed. Because H α traces the star formation and is observed using a fiber with 3 arcsec diameter which is similar to or smaller than the bulge radius, this result shows that for the galaxies with $\tau_{Bulge} > \tau_{Bar}$ the star formation occurs in the bulge region. These results support the scenario that the bars enhance the star formation in the center of the galaxies by accumulating the disk gas there.

In majority of all the sample, $(g\text{-}r)_{Bulge} > (g\text{-}r)_{Bar} > (g\text{-}r)_{Disk}$, which is translated to $\tau_{Bulge} < \tau_{Bar} < \tau_{Disk}$. However, there is a significant population of the galaxies for which $\tau_{Disk} > \tau_{Bulge} > \tau_{Bar}$. In any case, $|\tau_{Bulge} - \tau_{Bar}| < 2$ Gyr. The galaxies with $\tau_{Bar} < \tau_{Bulge}$ provide plausible candidates for the secular evolution scenario for bulge formation. The galaxy with $\tau_{Bulge} < \tau_{Bar} < \tau_{Disk}$ may have a star formation history that the bulge is formed by the dissipative collapse, the gas accretion from the halo forms the disk, and the bar is formed by the gravitational instability of the disk. However, the case with $\tau_{Bulge} < \tau_{Bar}$ does not necessarily exclude the secular evolution. There is a possibility as follows. A stellar disk with a negative color gradient is formed in the first place. Then, the gravitational instability of the disk produces a stellar bar, which subsequently turns into a bulge by the buckling instability of the bar. In this case, the negative color gradient of the initial disk will not be destroyed completely but preserved to some extent.

論文審査の結果の要旨

銀河の棒状構造(バー)は円盤銀河の約半数に見られ，円盤銀河の進化において重要な役割を果たすと考えられている。理論的には，バーは非軸対称構造であるために，星間ガスを重力トルクの作用で銀河中心部に集め，その結果バルジ形成に寄与するのではないかと考えられてきた(secular evolution model)。しかし，バーに関する従来の観測的研究は，サンプル数が小さく統計的有意性に劣ること，及びバーの検出と解析が視察など主観的な方法で行われていたこと，の2つの原因により，この理論的予想を検証することが不可能であった。本研究の目的は，従来の研究が抱えるこの2つの困難を解決することであった。まず，サンプル数を増大させるため，Sloan Digital Sky Survey という大規模全天サーベイから円盤銀河を抽出してサンプルとした。次に，客観的なバーの検出法として，銀河の等輝度線を楕円でフィットするellipse fit 法を使用した。これにより，バーのサイズ，偏平度，色等を定量的に求めることが可能となった。本研究はまず第一に，従来の研究で示唆されたバーのサイズおよび偏平度と銀河のハッブルタイプあるいは中心集中度の相関に関する結果をより優れた統計的有意性で確認した。次に，多数の銀河に対して初めてバー自体の色を求めることに成功した。バルジおよびディスクの色も同時に求め，種族合成の方法により，銀河の各成分の星形成史を明らかにした。その結果，大部分の銀河においては，バルジ，バー，ディスクの順に星形成のタイムスケールが増加することがわかった。しかし，中心集中度の低い晩期型の円盤銀河では，バルジがバーより青い銀河も存在し，これはsecular evolutionを示唆するものである。本研究は近傍銀河に対するバーの統計解析として最大規模のものであり，最近行われつつある遠方銀河のバー解析と並んで，棒状銀河の進化を直接観測的に解明するための手がかりを与えると期待される。以上の結果は，棒状銀河の進化と銀河バルジの起源を考察する上で有益な知見を与えており，神川えりかが自立して研究活動を行うために必要な高度な研究能力と学識を有することを示している。したがって，神川えりか提出の博士論文は，博士(理学)の学位論文として合格と認める。